Synergies between nuclear and solar thermal energy

FISA 2019 Technical workshop “Cross-cutting fission, fusion and non-nuclear energy synergies, challenges and opportunities”
6.6.2019

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EERA
European Energy Research Alliance
JPNM
JOINT PROGRAMME ON NUCLEAR MATERIALS

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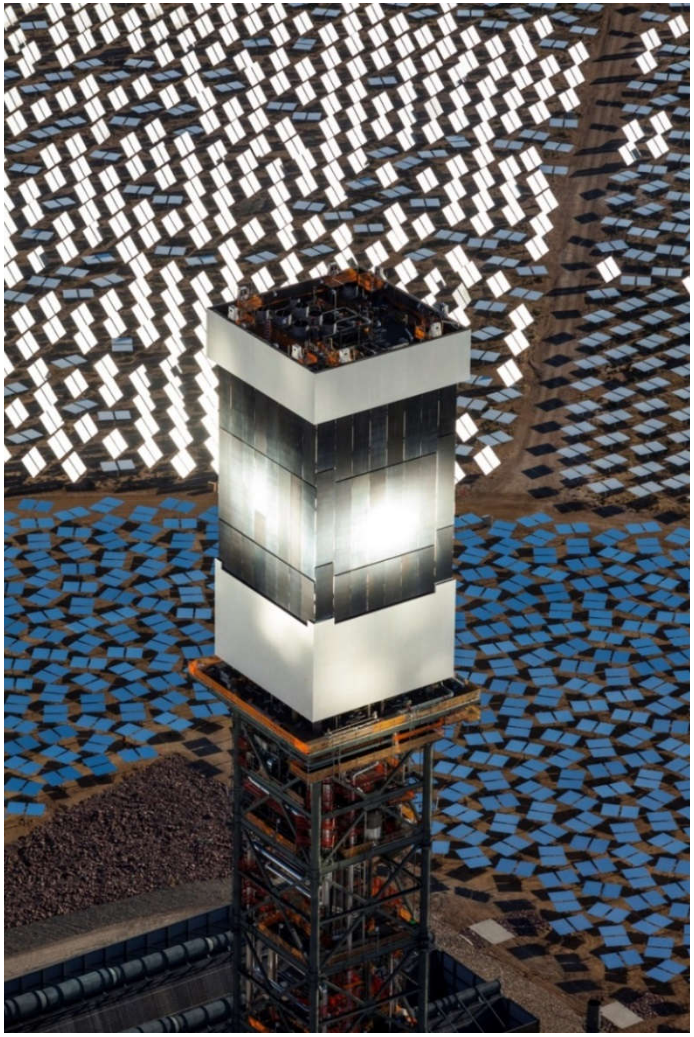


[Ivanpah, BrightSource]

Solar Technologies: PV and CSP

Image: SolEs

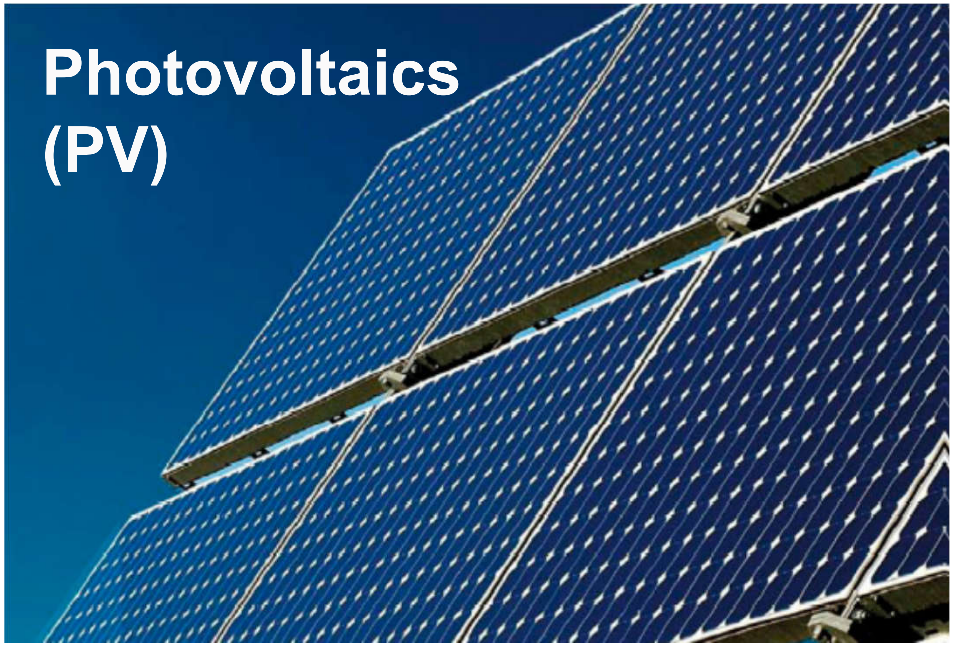
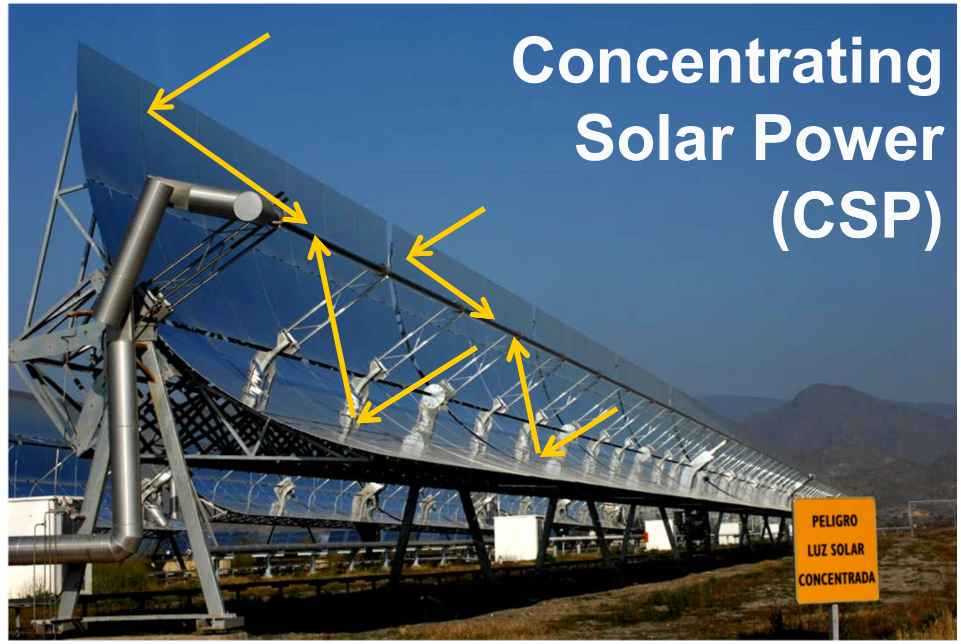


Image: DLR



Sunlight

↓ η ≈ 18% (multi-Si)

Electricity

Sunlight

↓

Heat ⇄ Thermal Heat Storage

↓

Electricity

η ≈ 14-20% (solar to electric)

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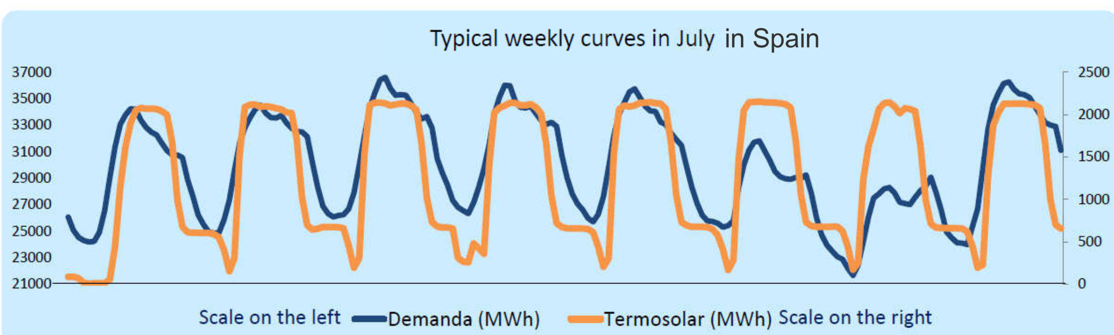
The value of thermal storage

- With increasing share of fluctuating sources in the grid, storage becomes necessary!
- CSP can follow demand curve and act as a complement to PV and wind, substantially increasing their penetration
- Thermal storage costs of 27 US$/kWh$_{th}$ (equivalent to 73 US$/kWh$_{el}$) are at least 4 times more cost efficient than battery storage
- Unreached storage capacity up to 5 GWh$_{th}$ by batteries
- State of the art:
  - storage in molten nitrate salts (KNO_3-$NaNO_3$, 40-60 wt.-%)
  - Lifetime: 30years, thermal losses: 1.8ºC/day
  - ~7-12h storage, 2 tank system
    - 290ºC / 400ºC → 11 years commercial experience
    - 290ºC / 565ºC → 8 years commercial experience



[PROTERMOSOLAR]

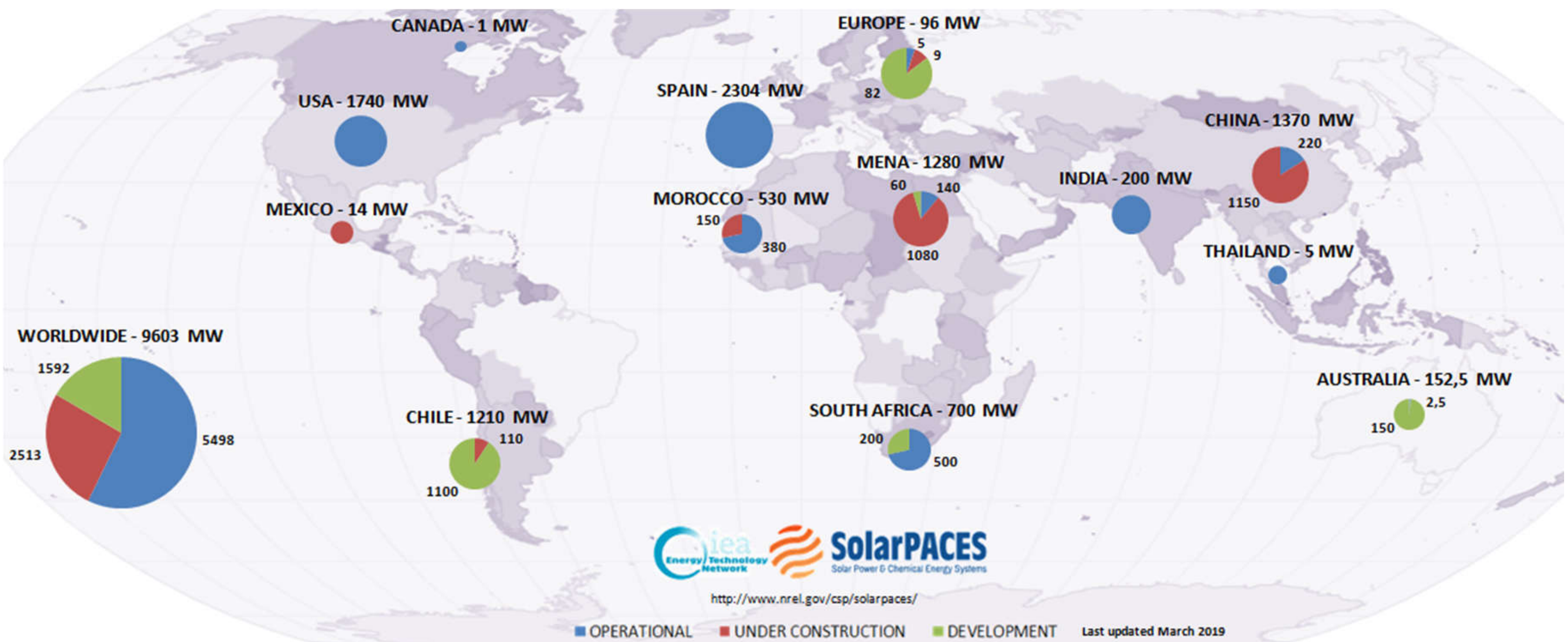
[10 hour storage, Crescent Dunes, Nevada]

[Image: Solar Millenium AG, 7.7h storage, Andasol, Spain]

[IRENA electricity storage costs 2017]

Some facts about Concentrated Solar Power

- Installed capacity in 2006: 0.5 GW, in 2019: **5.5 GW**.
- Around 40% of the capacity is installed in Spain. The 50 plants represent around **3% of the Spanish electricity generation mix**.
- IEA forecast: CSP share in the electricity mix could reach about **4% in Europe and 11% worldwide by 2030**.



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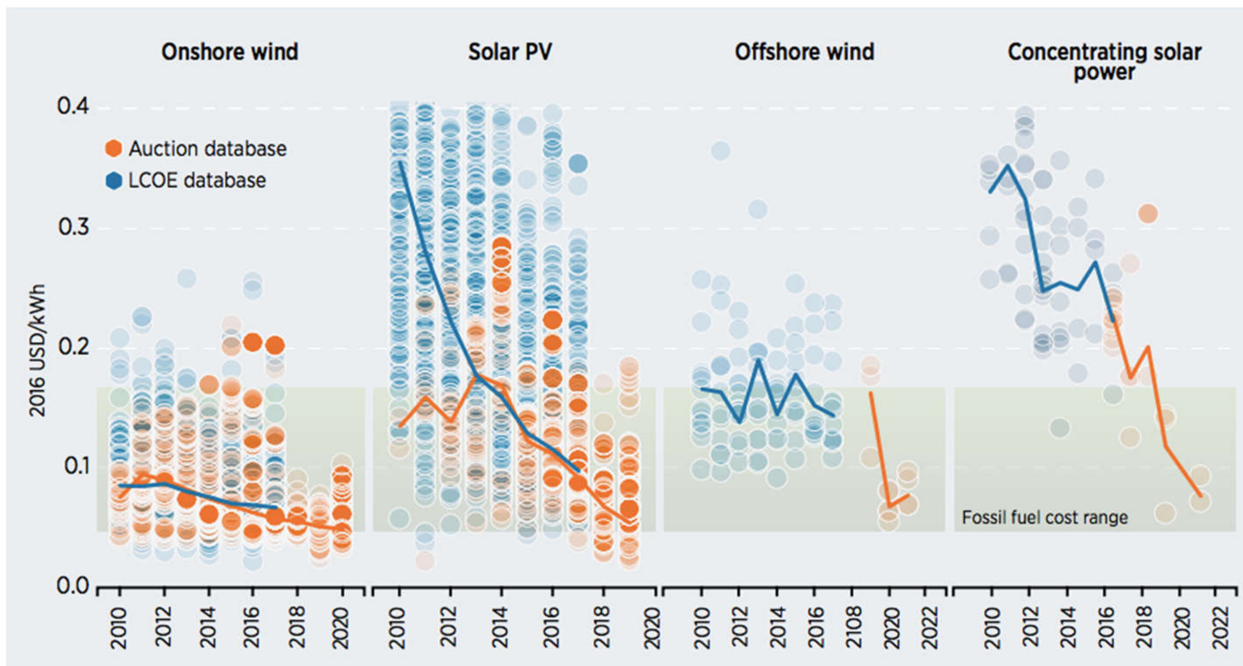
Cost of CSP

- Recent auction results suggest high learning rates. World record CSP lowest price is **6c€/kWh** for a 150 MW plant with 8 hours of thermal storage in Australia. **7c€/kWh** have been recently contracted in Dubai.

- PV prices are **<3c€/kWh**. Installed PV capacity worldwide ~400GW (2017)
  → as much as nuclear
  → 80 times more than CSP

- Complementing PV/CSP plants (such as Morocco's 800 MW Noor Midelt) are considered competitive to natural gas

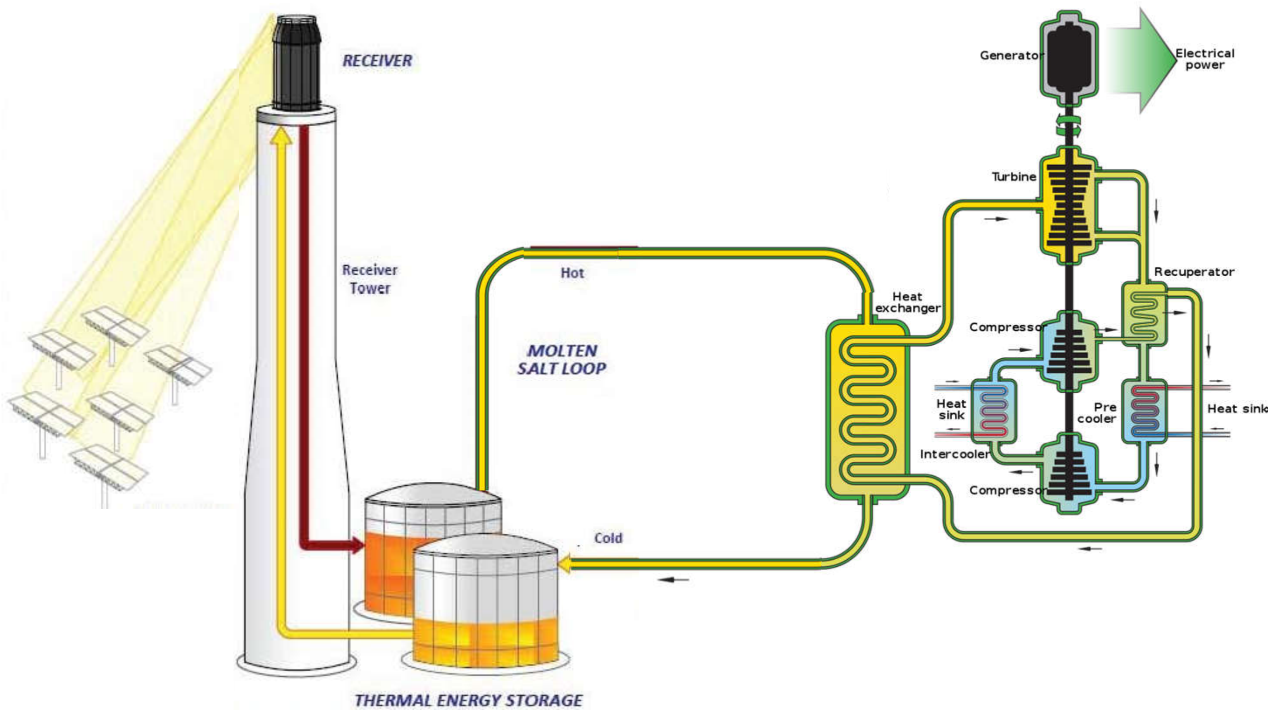
Levelized cost of electricity LCOE for projects 2010-2022



Source: IRENA Renewable Cost Database and Auctions Database.

Note: Each circle represents an individual project or an auction result where there was a single clearing price at auction. The centre of the circle is the value for the cost of each project on the Y axis. The thick lines are the global weighted average LCOE, or auction values, by year. For the LCOE data, the real WACC is 7.5% for OECD countries and China, and 10% for the rest of the world. The band represents the fossil fuel-fired power generation cost range.

Synergies between nuclear and CSP



Nuclear reactor is replaced by solar collector field and Thermal Energy Storage (TES)

Synergies:

- Power block
- Heat exchanger
- Heat transfer fluid
- Use of high temperature materials
- Testing and qualification methods

Image: Wikipedia and Solar Reserve

Types of CSP solar collector fields

Type	Parabolic Trough	Linear Fresnel	Solar Tower	Dish Systems
				
	Line Focus	Line Focus	Point Focus	Point Focus
Tracking	1-axis	1-axis	2-axis	2-axis
Conc.	C ~ 80	C ~ <80	C ~ 200 - 1000	C >1000
Temp.	200ºC – 500ºC	200ºC – 500ºC	500ºC – 1200ºC	700ºC (Stirling)
Power	50 - 280 MW_{el}	50 - 280 MW_{el}	10 – 150 MW_{el}	0.003 – 0.025 MW_{el}

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NOOR Ouarzazate Solar Complex (Morocco)

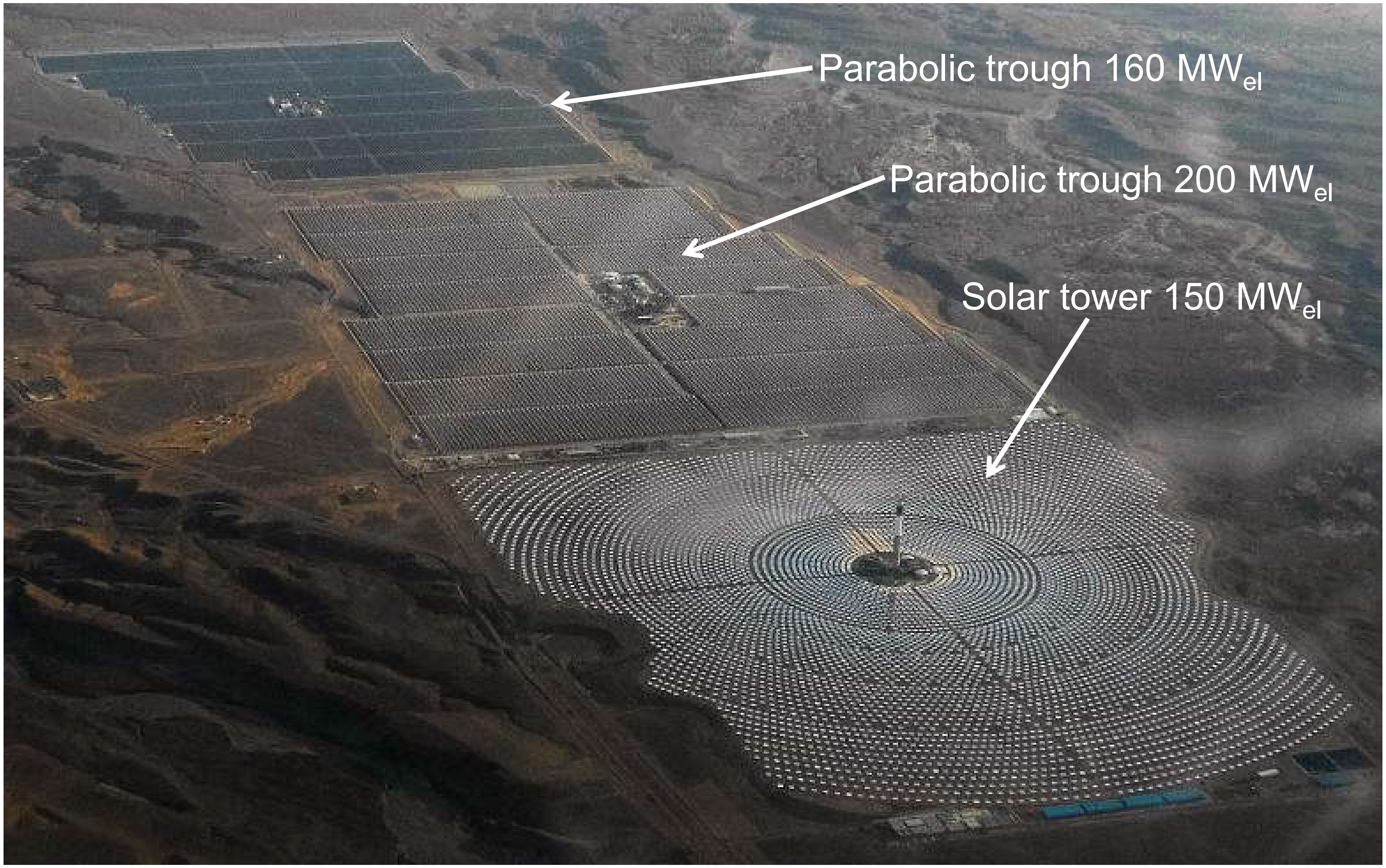


Image: Sener

Parabolic trough technology

Image: Sener

Vacuum

Absorber coating produced by sputtering processes
α=96%, ε=7.3% (400ºC)
Stable up to 600ºC in vacuum

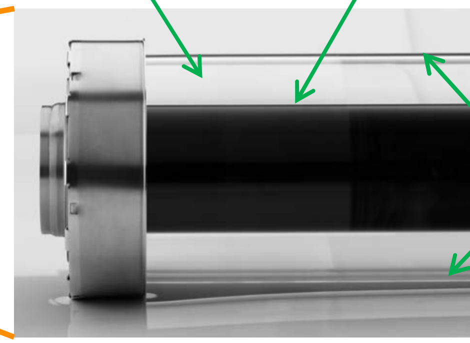


Image: Schott

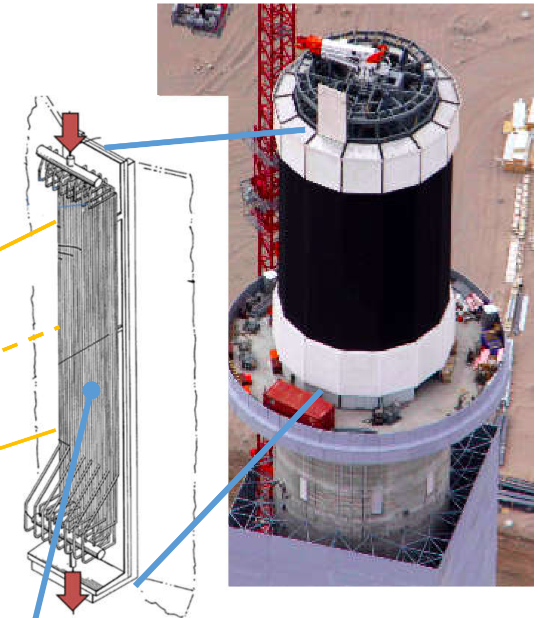
Glass tube with anti-reflective (AR) coating
τ ≈ 97%

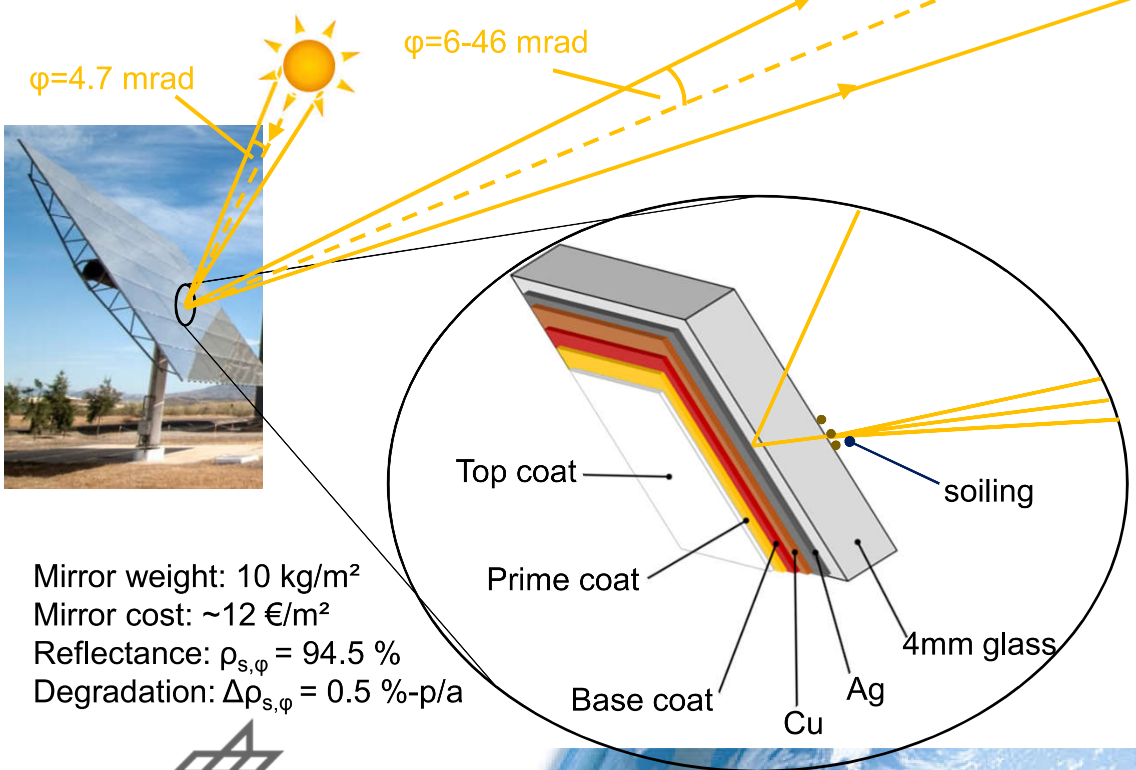
Steam temperature limited to 400ºC due to employed heat transfer fluid (e.g. Syltherm 800 or Therminol VP-1)

- Development of thermo-oils with higher upper temperature limit (e.g. 425ºC with Wacker Heliosol 5a)
- Direct steam (no storage)
- Molten salt (up to 565ºC)

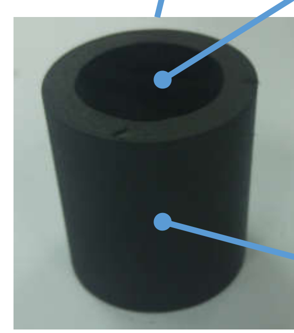
Molten salt solar towers

- Molten salt is displacing steam as state of the art heat transfer fluid
- Component efficiency and lifetime have a major impact on the levelized cost of electricity of the plant





Mirror weight: 10 kg/m²
Mirror cost: ~12 €/m²
Reflectance: $\rho_{s,\varphi}$ = 94.5 %
Degradation: $\Delta\rho_{s,\varphi}$ = 0.5 %-p/a



Ni-base alloy
T_{film} ≈ 600° C
Corrosion rate ~10µm/a in solar salt (40 wt-% KNO_3, 60 wt-% $NaNO_3$)

Pyromark 2500
α_s = 97 %
$\varepsilon_{750°C}$ = 82%
$\eta_{250kW/m^2,750°C}$ = 77%
$\Delta\alpha_s$ = 2 %-p/a
T_{skin} ≈ 750ºC

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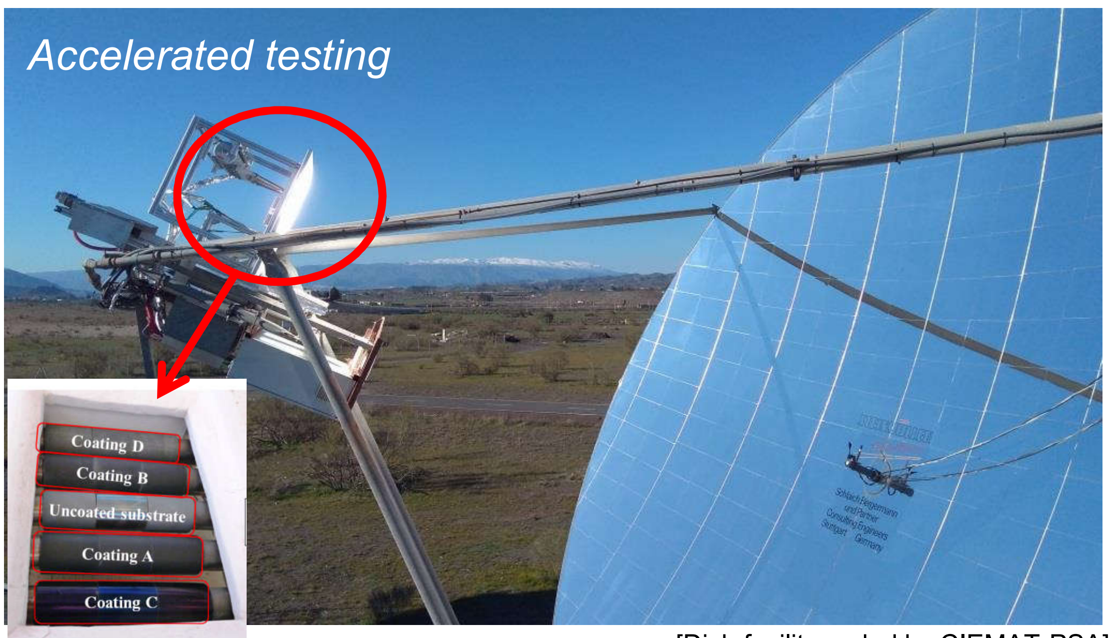
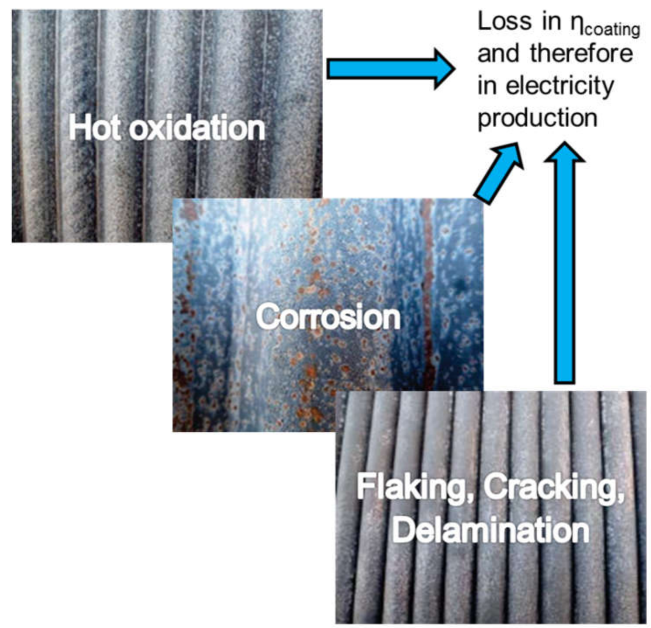
Outer surface of tubular receivers

Coating requirements

- Solar absorptance > 96%
- Low thermal emittance
- Skin temperature: up to 750ºC
- High thermal conductivity
- Hot oxidation resistance
- Environmental corrosion resistance during night / plant shutdown
- Erosion resistance to dust and sand storms
- Chemical inertness to dust deposits (also at high temperature)
- Possibility for recoating on top of tower
- Possibility to cure paint coatings using solar energy
- Lifetime: up to 30 years



[Dish facility ceded by CIEMAT-PSA]



© BrightSource

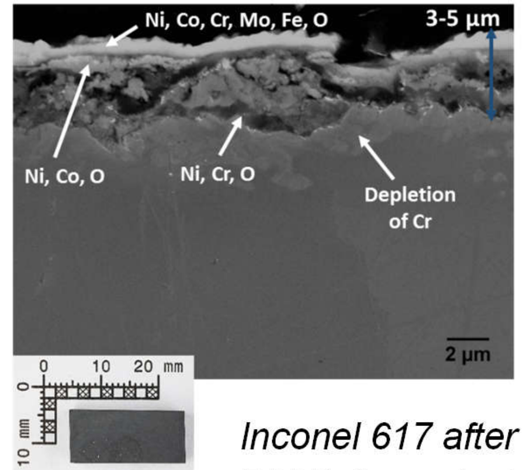
Inner surface of tubular receivers

Corrosion mechanisms:

- Cr-depletion
- Complex oxide scale formation
- Accelerated corrosion by oxides of decomposed salt

$NO_{3}^{-}{}_{(liquid)} \leftrightarrow NO_{2}^{-}{}_{(liquid)} + ½\, O_{2(gas)}$

$a\, NO_{2}^{-}{}_{(liquid)} + b\, NO_{3}^{-}{}_{(liquid)} \leftrightarrow v\, O^{2-}{}_{(liquid)} + w\, NO_{2(gas)} + x\, NO_{(gas)} + y\, N_{2(gas)} + z\, O_{2(gas)}$



Inconel 617 after 5000h in contact with solar salt at 580ºC

[Univ. Compultense Madrid]

Annual corrosion rate [µm/ year] of different alloys in contact with solar salt (KNO_3-$NaNO_3$, 40-60wt.%)

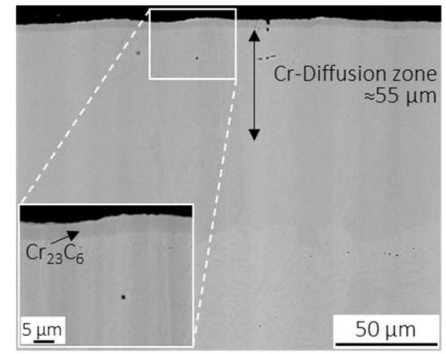
T [°C]	T91 9% Cr <0.04% Ni	VM12 12% Cr <0.4% Ni	316L 17% Cr 12% Ni	321H 19% Cr 12% Ni	347 19% Cr 13% Ni	Haynes 230 22% Cr 57% Ni	Inconel 625 23% Cr 58% Ni
400				1.0	0.7	0.5	0.2
500				7.1	4.6	1.8	0.5
550			8.6	9.0			
580	192.7	87.6					
600	236.1			15.9	10.4	19.8	12.7
680				914.9		688	594

[T. Bauer, DLR, 2018] [A. Gomes et al. https://doi.org/10.1016/j.solener.2018.11.019] [SANDIA, INTA, Univ. Compultense Madrid, CIEMAT, LNEG]

Coatings for molten salt receivers

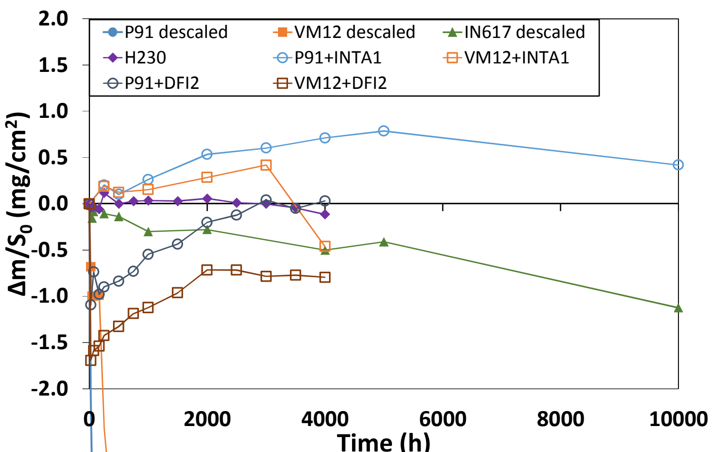
INTA and DECHEMA are developing aluminide and Cr-diffusion **coatings for corrosion protection**. Only negligible mass loss was detected on coated samples in contact with solar salt at 560 and 580ºC for 10,000h.

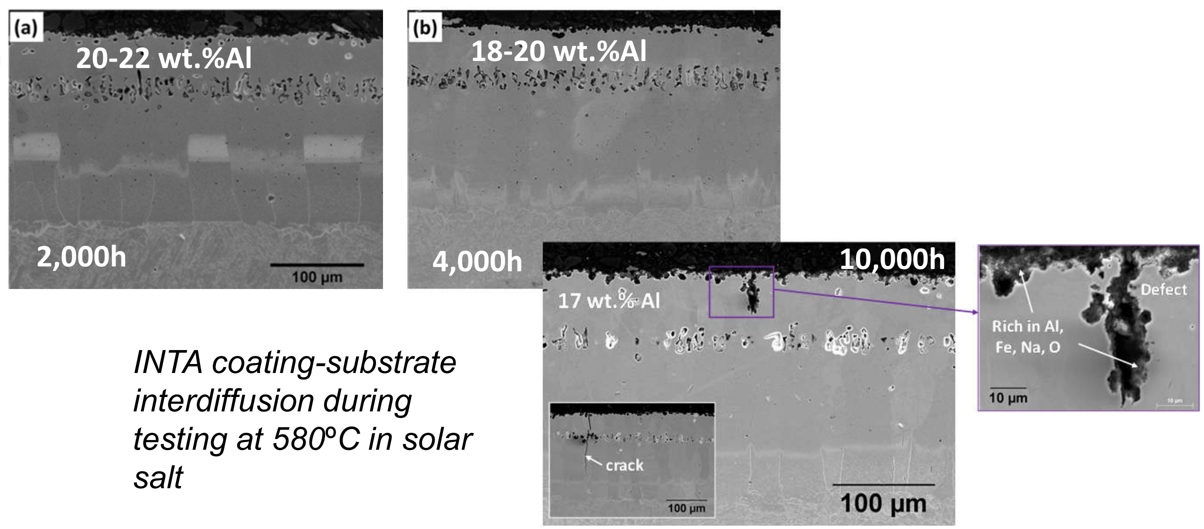
- Minimum changes in coating thickness and surface Al-concentration for INTA coating
- DECHEMA coating experiences an initial mass loss (dissolution of $Cr_{23}C_6$ into the salt), then stable oxide scale (Cr-reservoir re-heals the oxide scale).



DECHEMA Cr-diffusion coating

Static testing in solar salt at 580° C





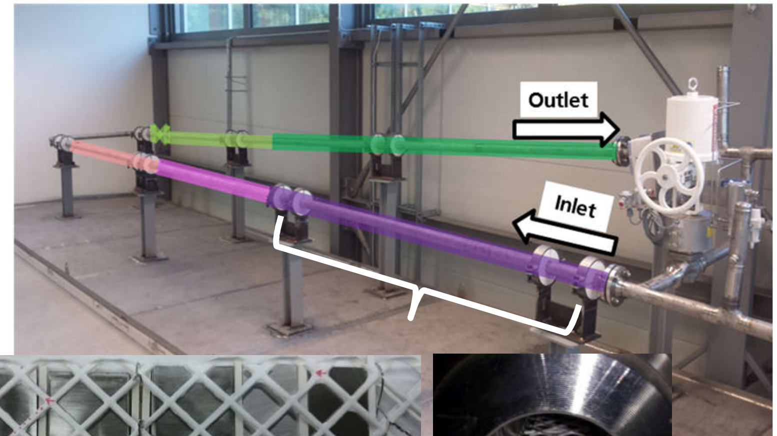
INTA coating-substrate interdiffusion during testing at 580ºC in solar salt

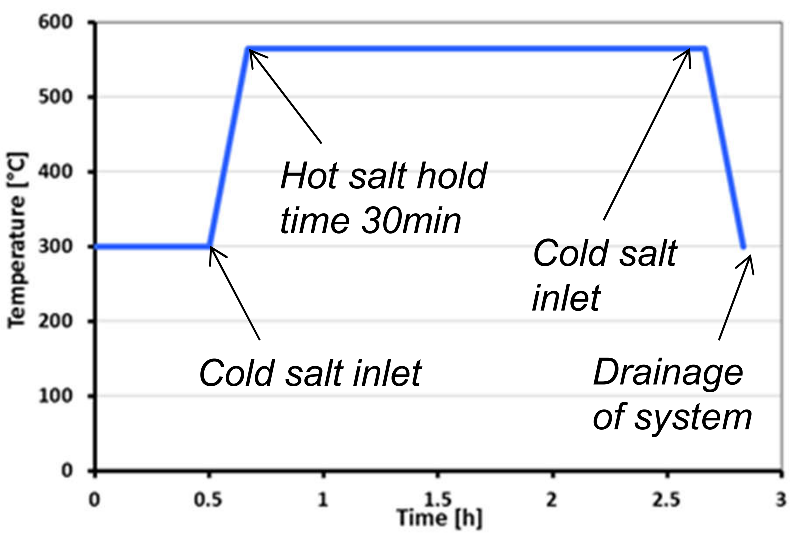
[A. Agüero, INTA, M. Galetz, DECHEMA, 2019]

RAISELIFE DLR

Dynamic testing of corrosion in molten solar salt

Test facility for thermal energy storage in molten salts (TESIS) at DLR in Cologne, Germany

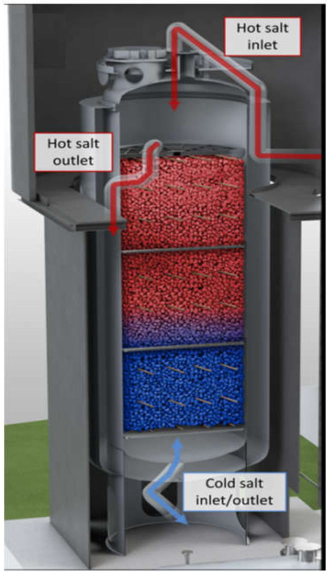




- Molten salt mass flow: 8 kg/s (1.97 m/s)
- 21 material types to be tested (116 samples)
- 500 cyles will be conducted (equivalent to approx. 1 year of operation)
- Testing will start this month

Further research topics related to molten solar salt

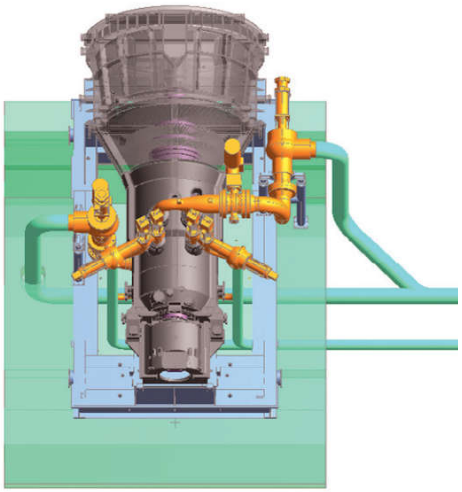
- Increase reliability of hot tank (565ºC) to meet the 30 year lifetime target
- Improving lifetime of components (valves, gaskets, pumps)
- Operation at 600ºC keeping salt degradation and within acceptable limits
- Consideration of occupational safety and environmental aspects (Cr-VI enrichment of salts, nitrogen oxide gas release)
- Development of thermocline molten salt tank technology
- Investigation of high energy density filler materials to increase energy density and reduce cost



[T. Bauer, DLR, 2018]

Power block

- State of the art steam turbines for CSP:
  - large number of starts (daily)
  - rapid start-up
  - typical size of 50 – 250 MW, max. steam inlet: 180 bar / 565ºC
- Water or air cooled condenser

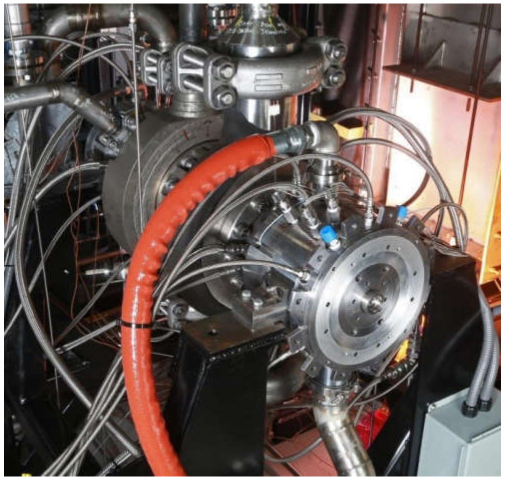


[Siemens]

- DoE has selected the supercritical carbon dioxide (sCO_2) Brayton cycle as the best-fit power cycle for increasing CSP system thermo-electric conversion efficiency. Target: 50%

  → temperatures >700ºC are required

  → alternative HTF is required

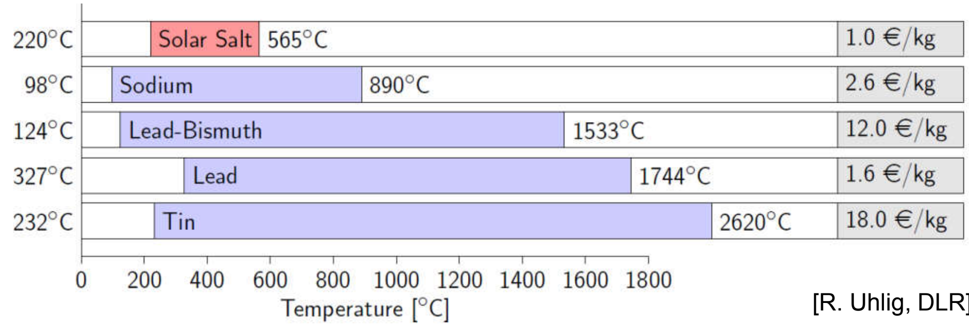


First 10 MW sCO_2 turbine built, approaching 50% efficiency

[GE & SWRI]

Next generation CSP plants (Gen3)

- HTF with higher temperature range than Solar Salt is required to feed sCO_2 cycle

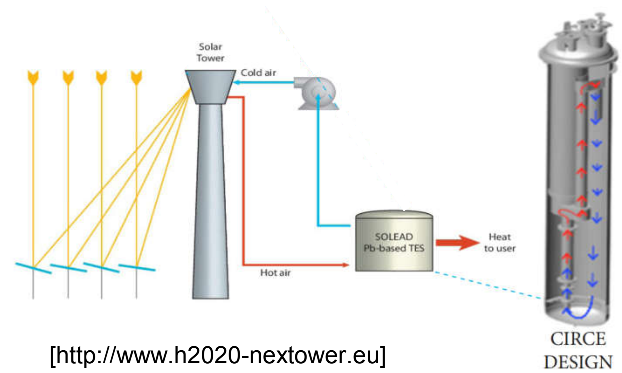


[R. Uhlig, DLR]

- First experiments with liquid sodium and solar towers were carried out in 1980s in USA and Spain.
- 1.1 MW_{el} pilot plant using sodium as HTF was commissioned in 2018 in Jemalong, Australia.
- 30 MW_{el} commercial plant is under development.

[Vast Solar]

- H2020 NEXTOWER project: coupling a liquid lead storage system with an air-based CSP plant (up to 800ºC)



[http://www.h2020-nextower.eu]

Next generation CSP plants (Gen3)

DEO identified 3 pathways, each of them containing substantial technological, economical or reliability risk

Collector Field
- Cost <\$75/m^2
- Concentration ratio >50
- Operable in 35-mph winds
- Optical error <3.0 mrad
- 30-year lifetime

	Molten Salt	Falling Particle	Gas Phase
Receiver *Cost < \$150/kWth* *Thermal Efficiency > 90%* *Exit Temperature > 720°C* *10,000 cycle lifetime*	• Similarities to prior demonstrations • Allowance for corrosive attack required	• Most challenging to achieve high thermal efficiency	• High-pressure fatigue challenges • Absorptivity control and thermal loss management
Material & Support *Cost < \$1/kg* *Operable range from 250°C to 800°C*	• Potentially chloride or carbonate salt blends; ideal material not determined • Corrosion concerns dominate	• Suitable materials readily exist	• Minimize pressure drop • Corrosion risk retirement
Thermal Storage *Cost < \$15/kW$_{th}$* *99% energetic efficiency* *95% exergetic efficiency*	• Direct or indirect storage may be superior	• Particles likely double as efficient sensible thermal storage	• Indirect storage required • Cost includes fluid to storage thermal exchange
HTF to sCO_2 Heat Exchanger	• Challenging to simultaneously handle corrosive attack and high-pressure working fluid	• Possibly greatest challenge • Cost and efficiency concerns dominate	• Not applicable

Supercritical CO_2 Brayton Cycle
- Net thermal-to-electric efficiency > 50%
- Power-cycle system cost < \$900/kW$_e$
- Dry-cooled heat sink at 40° C ambient
- Turbine inlet temperature ≥ 700°C

[Mehos et al. 2017: Concentrating Solar Power Gen3 Demonstration Roadmap https://www.nrel.gov/docs/fy17osti/67464.pdf]

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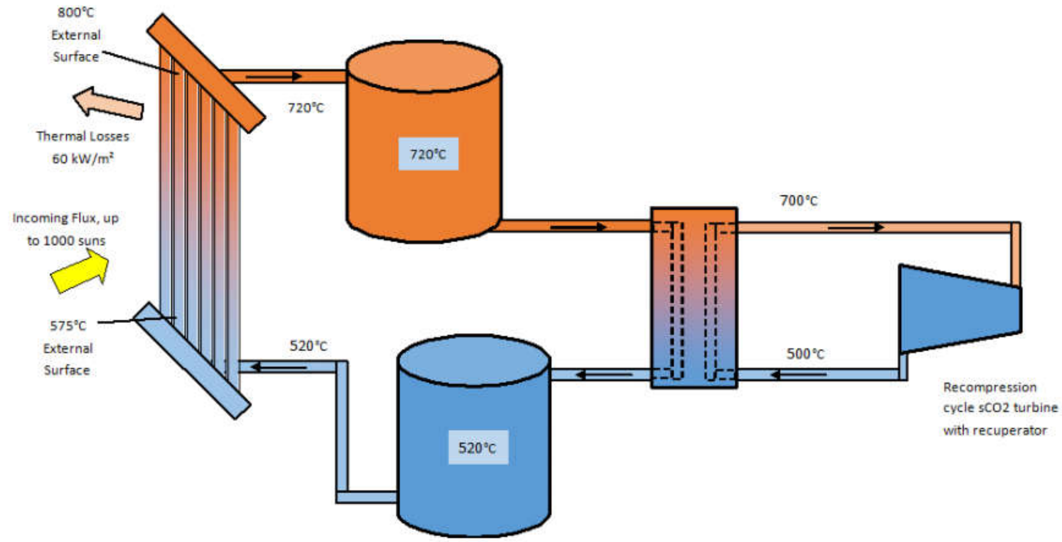
Molten Salt Pathway

- Most familiar approach (similar receiver design than current state of the art)
- Raising hot salt temperature to 720ºC brings material challenges
- Selection of compatible high temperature molten salt and structural materials is needed
- Understanding of corrosion mechanisms in carbonate and chloride salts is needed
- Components like pumps and valves need to be developed



[Concentrating Solar Power Gen3 Demonstration Roadmap]

Possible salt candidates

Salt System (Composition in wt%)	T_m (°C)	T_{max} (°C)	H (J g^{-1})	c_p (J g^{-1}K^{-1})	ρ (g cm^{-3})	$\rho \cdot c_p$ (J cm^{-3} K^{-1})
KNO_3-$NaNO_{3(solar)}$ (40-60)	240[b]	530-565	113	1.55[a]	1.84[a]	2.85[a]
K_2CO_3-Li_2CO_3-Na_2CO_3 (35-32-33)	397	>650	273	1.85[c]	1.98[c]	3.66[c]
KCl-LiCl (55-45)	355	>700	236	1.20[c]	1.65[c]	1.98[c]
KCl-$MgCl_2$ (61-39)	426	>700	355	1.15[c]	1.92[c]	2.22[c]
NaF-$NaBF_4$ (3-97)	385	700	N/A	1.51[c]	1.75[c]	2.65[c]
KF-ZrF_4 (32-68)	390	>700	N/A	1.05[c]	2.80[c]	2.94[c]
KF-LiF-NaF (59-29-12)	454	>700	400	1.89[c]	2.02[c]	3.82[c]

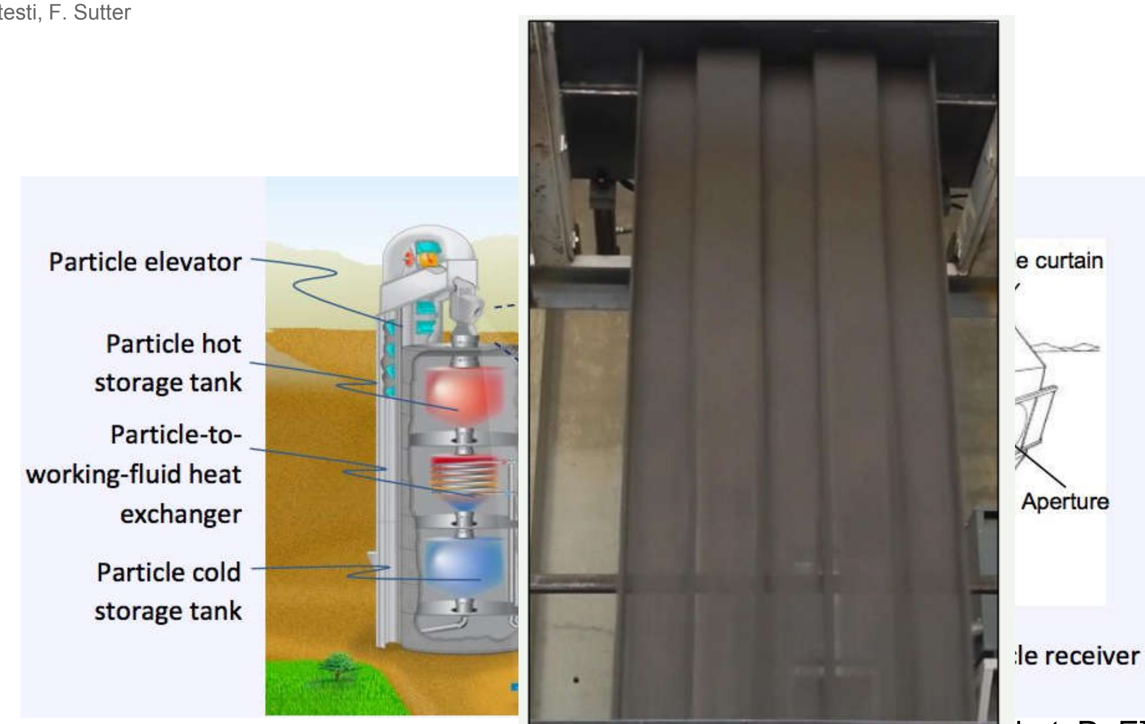
The table contains results from own measurements and literature values [6–17].
[a]Values at 400 °C.
[b]Approximate liquidus temperature.
[c]Values at 700 °C.

[T. Bauer, DLR, Molten Salts Chemistry, 2013]

Falling Particle Pathway

Benefits:

- Direct absorption of particles - no need for expensive alloys, estimated cost reduction potential of 16% compared to Molten Salt Towers
- No freezing issues with particles
- No flux limits

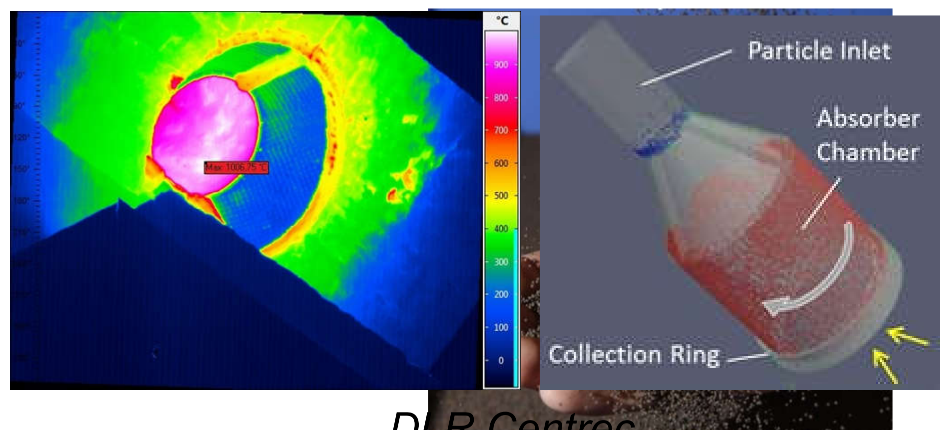


[image: Sunshot, DoE]

Sandia falling particle receiver

Challenges:

- Efficient particle heating, flow control
- Particle attrition and erosion of metallic structures at elevated temperatures
- Particle to sCO_2 heat exchanger efficiency

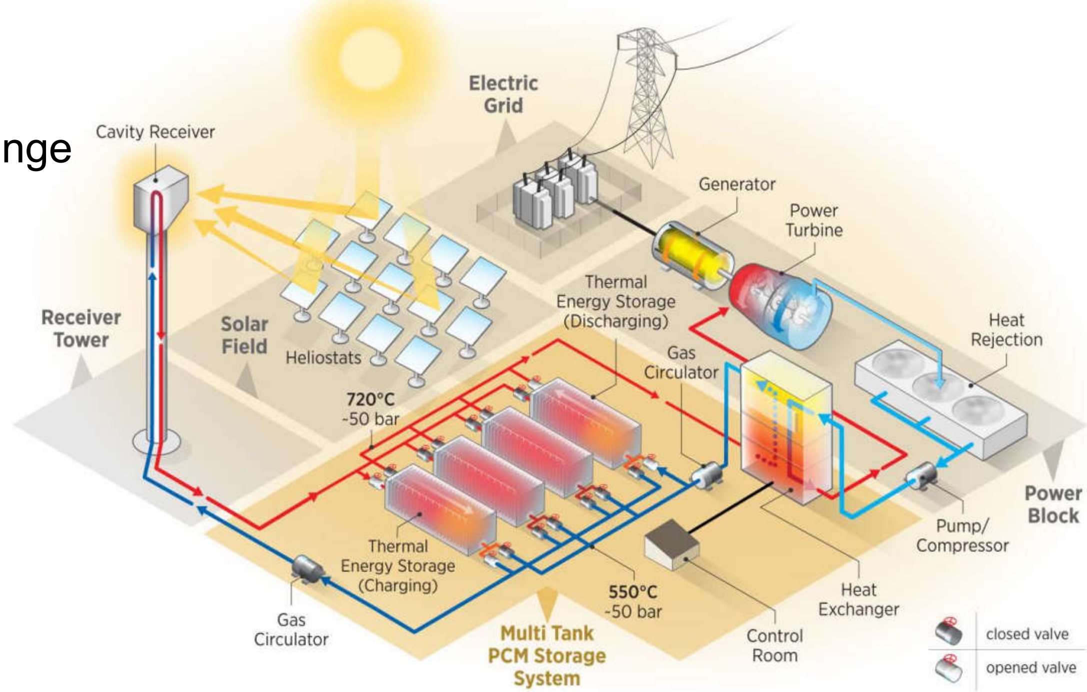


DLR Centrec

Gas Phase Pathway

Benefits:

- Stability of HTF over temperature range → no freezing issues
- Inert interaction with pipes
- Minimal environmental and safety hazards



Usage of stable gaseous HTF such as CO_2, Helium or Argon at ~75 bar

Challenges:

- Requires indirect storage (phase change material or particle storage)
- Power consumption for fluid circulation
- Gases have inferior heat transfer
- High cost and low stress resistance of high temperature alloys >700ºC

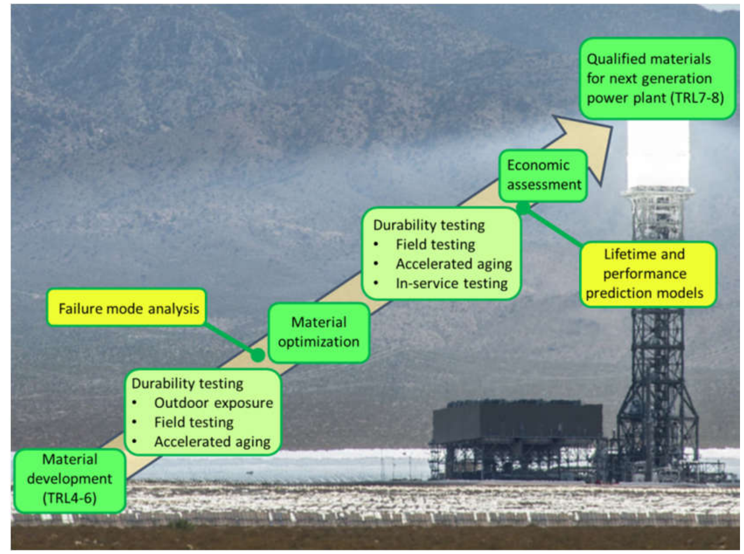
[Concentrating Solar Power Gen3 Demonstration Roadmap]

Summary

- CSP share in the energy mix is expected to grow in the coming years, providing flexibility to compensate fluctuating sources like PV or wind.
- The use of molten nitrates as Thermal Energy Storage and Heat Transfer Fluid (HTF) up to 565ºC has become state of the art, although the technology needs further improvement (reliability, cost, higher temperature)
- The supercritical carbon dioxide (sCO2) Brayton cycle was identified as the best-fit power cycle for increasing CSP efficiency
- Promising HTFs to deliver >700ºC for CSP Gen3 plants are: chloride molten salts, particles, gaseous energy carriers or liquid metals.

Outlook

- Workshop of H2020 project RAISELIFE on CSP materials with increased service lifetime to be held on 21st of November 2019 in Düsseldorf (information and registration soon available under www.raiselife.eu)



RAISELIFE

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 686008, project RAISELIFE.

- Collaboration within future Horizon 2020 project proposals?
  - LC-SC3-RES-35-2020: Reduce the cost and increase performance and reliability of CSP plants
  - LC-SC3-CC-9-2020: Industrial (Waste) Heat-to-Power conversion

Thank you for your attention!

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OPAC (Optical Aging Characterization) laboratory in Tabernas, Spain

Acknowledgements:

J. Fernández-Reche and CIEMAT for collaboration on PSA and ceding the dish concentrator facilities for durability testing.

T. Bauer and DLR-TT colleagues for conducting dynamic molten salt corrosion test